

INVESTIGATION OF THE PRESSURE DISTRIBUTION OF METAL ON THE ROLLS
DURING THE ROLLING PROCESS

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INVESTIGATION OF THE PRESSURE DISTRIBUTION OF METAL ON THE ROLLS
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ABSTRACT

Derivation of an equation for stresses developing during rolling, as a function of rolling rate, size of the rolls, geometry of the product, and friction. A preliminary comparison of theoretical and experimental results shows good agreement.

A theoretic and experimental study of the specific pressure distribution along the capture arc and the metal cross section at the opening of the rolls is of great interest, and makes it possible to study plastic deformation during rolling. A knowledge of the laws governing metal deformation during rolling is necessary, both for planning and constructing new rolling mills, and for developing existing mills. It also makes it possible to correctly construct the main operational units of the mill and to select the most advantageous technological rolling process. /83*

Up to the present time, there has not been sufficient research on many problems relating to the nature of physico-mechanical processes occurring in a metal during large plastic deformations. The assumptions advanced by different researchers on this problem do not have a comprehensive, scientific basis, since the theoretical conclusions do not fully correspond to the experimental data.

Existing rolling theories do not provide the analytical dependence of stress on the factors influencing it. Therefore, equations showing the influence of the stress state on the specific pressure have been approximately derived. Curves showing the distribution of specific pressures during rolling, which were compiled in accordance with the Karman theory, have not been substantiated by experimental diagrams. The theoretical curves have two concave branches which rise toward the critical cross-section and which form a peak-like curve, while the experimental curves have convex branches with a dome-shaped apex. The lack of agreement between the theoretical curves and the experimental curves may

* Numbers given in the margin indicate pagination in the original foreign text.

primarily be explained by the fact that the law governing the friction on the roll surfaces in the deformation zone is not taken into account correctly in the theoretical formulas based on the Karman theory.

The main problem encountered in rolling, which underlies any future, comprehensive research, is the study of a theory for the metal deformation mechanism in rolls during rolling. This report makes an attempt to formulate analytically the relationship between stress during rolling and the factors influencing it: the rolling rate, the geometric dimensions of the rolls and the bar, and the friction between the rolls and the metal, etc. /84

Let us examine the rolling process, in the case when the rolls are cylindrical and when the width of the bar to be rolled is several times greater than the length of the capture arc. Therefore, the influence of the widening can be disregarded. It may thus be assumed that this is a two-dimensional problem. For this purpose, let us employ the equation of plasticity for two-dimensional deformation

$$\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2 = k^2, \quad (1)$$

where, k is the resistance to pure shear;

$$k = \frac{\sigma_\phi}{\sqrt{3}} \approx 0,57 n_t n_H n_v \sigma_s;$$

σ_ϕ - actual resistance to distortion during linear deformation, i.e., during simple contraction or expansion with allowance for the influence of temperature, deformation rate, and cold hardening;

n_t, n_H, n_v - coefficients taking into account the influence of temperature, cold hardening, and deformation rate on resistance to deformation;

σ_s - yield point.

When the stress direction σ_x and σ_y coincides with the main axes of the stress, the plasticity equation (1) assumes the following form: /85

$$\sigma_1 - \sigma_3 = 2k. \quad (2)$$

It may be seen from the equation (2) that the beginning of plastic deformation is not determined by the absolute values of normal stresses, but rather by their difference. We may distinguish a certain element with the dimensions dx in the cross-section h_x (Figure 1).

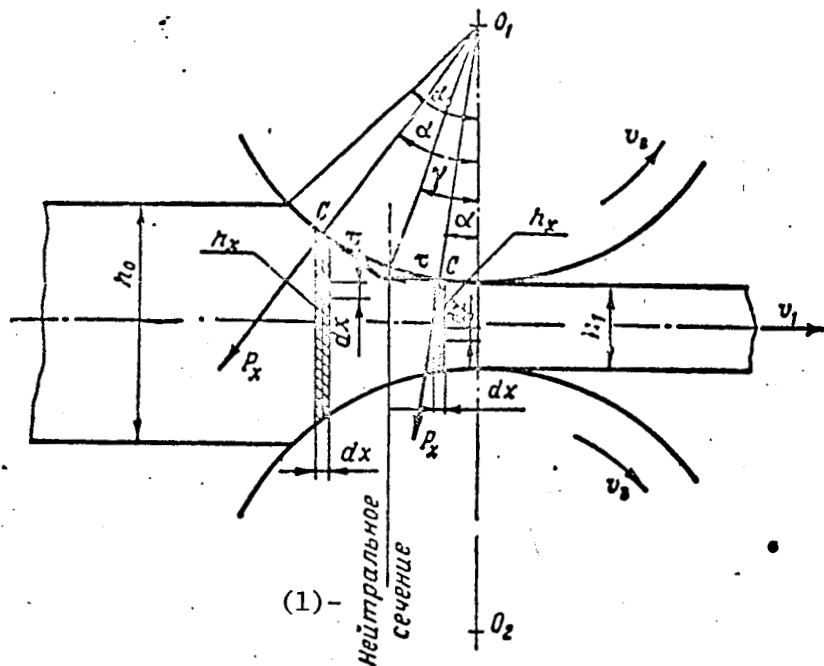


Figure 1

Diagram of Stress Distribution During Rolling

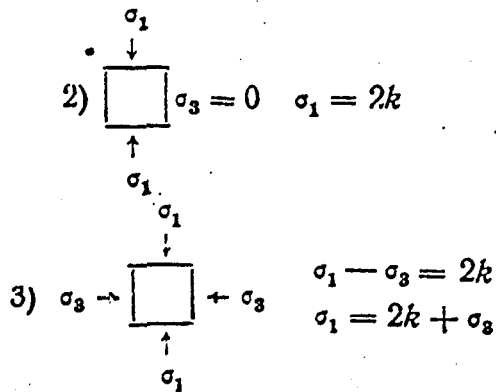
(1) - Neutral cross-section

For the element selected, we may take the vertical and horizontal stresses σ_1 and σ_3 as the main stresses; the main stress σ_3 coincides with σ_x ($\sigma_3 = \sigma_x$). Equation (2) may now be re-written as follows:

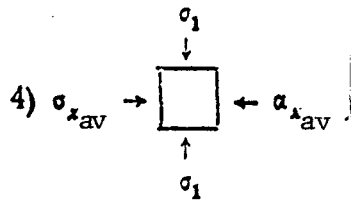
$$\sigma_1 = 2k + \sigma_x. \quad (3)$$

There are two unknowns in equation (3). In order to solve this equation, we must eliminate one unknown, and in order to do this let us first examine the diagrams of the stress state at the deformation center during two-dimensional rolling

$$1) \begin{array}{c} \sigma_1 \\ \downarrow \\ \sigma_3 \leftarrow \boxed{} \rightarrow \sigma_3 \\ \uparrow \\ \sigma_1 \end{array} \quad \begin{array}{l} \sigma_1 + \sigma_3 = 2k \\ \sigma_1 = 2k - \sigma_3 \end{array}$$



Taking the influence of the outer zones into account - i.e., the zones adjacent to the geometric center of deformation - we may note that diagram 3 is characteristic for rolling, as it results along the entire height of the cross-section h_x , i.e.,



From this point on, in order to derive the formula we shall not /86 be interested in the true value of σ_x along the cross-section height h_x , i.e., $\sigma_x = f(h_x)$. In order to derive it, we shall confine ourselves to the averaged stress $\sigma_{x \text{ av}}$. Let us re-write equation (3) with $\sigma'_{x \text{ av}}$:

$$\sigma_1 = 2k + \sigma_{x \text{ av}}. \quad (4)$$

In order to indicate the stress $\sigma_{x \text{ av}}$ in diagram 4, we need only assume the same stress, only directed toward the other side. In the vector form, this may be expressed:

$$-\vec{\sigma} = \vec{\sigma}_{x \text{ av}}.$$

The stress $\sigma_{x \text{ av}} = \sigma$ has an influence along the entire cross-section area. Consequently, the product $\sigma_{x \text{ av}} h_x b$ is none other than the force P_x :

$$P_x = \sigma_{x \text{ av}} h_x b, \quad (4')$$

where h_x is the cross-section height;

b - Width of the bar being rolled.

Based on the given rolling parameters, we may find the average velocity of the bar at the deformation center in the direction of the abscissa x , and then the acceleration in the same direction. The volume per second of the metal being rolled, passing through any cross-section, must be constant:

$$V = v_{xav} h_x b = v_1 h_1 b, \quad (5)$$

where V_{xav} - mean velocity of the metal in the cross-section under consideration;

h_x - cross-section height (of the bar);

b - cross-section width (of the bar);

v_1 - average velocity of the bar cross-section at the roll outputs;

h_1 - bar height at the roll outputs.

We may find the mean metal velocity for the cross-section under consideration from equation (5):

$$v_{xav} = \frac{v_1 h_1}{h_x}. \quad (6)$$

From Figure 2 we may find h_x by means of the angle α ($h_x = f(\alpha)$):

$$h_x = h_1 + 2r(1 - \cos \alpha). \quad (7)$$

Solving the system of equations (6 and 7), we may find the mean velocity of the cross-section motion h_x :

$$v_{xav} = \frac{v_1 h_1}{h_1 + 2r(1 - \cos \alpha)}. \quad (8)$$

In order to determine the mean acceleration of the metal in the cross-section h_x in the direction of the axis x , we must take the first derivative of the mean velocity with respect to time

$$a_{av} = \frac{dv_{xav}}{dt} = - \frac{2rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt}. \quad (9)$$

Let us employ the second law of Newton in order to determine the stress σ_{xav} ($P = ma$). The force P_x [equation (4')] and the acceleration a_{av} [equation (9)] may be expressed by the corresponding parameters. We must now find the mass m . Since we shall solve this like a two-dimensional

problem, in order that shear may occur along the horizontal axis, it is necessary to overcome the resistance which is proportional to the magnitude of k . The force P'_x is required in order to overcome this resistance along the entire cross-section surface.

The metal in the deformation zone moves with an average acceleration of a_{av} . Therefore, the force of inertia P''_x exists during rolling. In addition to these two forces (P'_x and P''_x), the friction force F_{fr} has an influence along the contact surface. Let us balance all of the forces given above by the force P_x :

$$P_x = P'_x + P''_x \pm F_{fr} \cos \alpha. \quad (10)$$

The plus sign in front of the third term in the right part of the equation pertains to the trailing zone, and the minus sign pertains to the advancing zone. Let us determine the components P'_x , P''_x and F_{fr} :

$$P'_x = \frac{k}{g} h_x b a_{av}; \quad (11)$$

$$P''_x = n \rho v h_x b a_{av}, \quad (12)$$

where ρ is the density in g/cm^3 ;

$$F_{av} = \frac{\tau}{g} \frac{dx}{\cos \alpha} b a_{av}. \quad (13)$$

Let us substitute the values P'_x , P''_x and F_{fr} from equations (11), (12), (13) in equation (10):

$$P_x = \frac{k}{g} h_x b a_{av} + n \rho v h_x b a_{av} \pm \frac{\tau}{g} dx b a_{av}. \quad (14)$$

The third component in the right part of equation (14) will equal zero, since $\frac{\tau}{g} b a_{av}$ is a finite quantity, and dx is infinitely small of the second order. Consequently, the entire expression will strive to zero. We then have

$$P_x = \frac{k}{g} h_x b a_{av} + n \rho v h_x b a_{av}. \quad (15)$$

Let us divide both parts of equation (15) by the product $h_x b$, i.e., by the surface of the cross-section under consideration:

$$\sigma_{xav} = -\frac{k}{g} \frac{2rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt} - \frac{1}{g \cdot 10^5} \rho v \frac{2rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt}.$$

When this equation is solved, the minus sign is cancelled, since negative values of the angle α are substituted in the equation (see Figure 1). From this point on, we shall substitute absolute values of the angle α . Taking this fact into account, let us re-write equation (18) with the plus sign

$$\sigma_{xav} = \left(k + \frac{\rho v}{10^5}\right) \frac{2rv_1 h_1 \sin \alpha}{g[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt}. \quad (19)$$

Due to the fact that the second term ($\rho v/10^5$) in the right part of equation (19) is insignificant as compared with the first (k), we may disregard it. We then have

$$\sigma_{xav} = \frac{2k}{g} \frac{rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt}. \quad (20)$$

Let us write the following equation of plasticity for the element /89 having the dimension dx (see Figure 1):

$$\begin{aligned} \sigma_1 &= 2k + \tau_{xav}; \\ \sigma_1 &= 2k + \frac{2k}{g} \frac{rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} \frac{d\alpha}{dt}. \end{aligned} \quad (21)$$

The main stress σ_1' will act along the vertical at the point C

$$\begin{aligned} \sigma_1' dx &= p_x \frac{dx}{\cos \alpha} \cos \alpha \pm \tau \frac{dx}{\cos \alpha} \sin \alpha; \\ \sigma_1' &= \left(p_x dx \pm \tau \frac{dx}{\cos \alpha} \sin \alpha\right) \frac{1}{dx}. \end{aligned} \quad (22)$$

Since the second term in the right part of equation (22) is significantly less than the first term, it may be discarded without entailing any large amount of error, and we then have

$$\sigma_1' = p_x.$$

The stress σ_{xav} acts upon the surface 1×1 mm, and during rolling there is deformation simultaneously along the entire height of the cross-section h_x . Therefore, the stress in the direction of the axis x for the entire cross-section increases by a factor of h_x , while in this case h_x has the dimensions in mm:

$$\sigma'_{x_{av}} = \sigma_{x_{av}} h_x. \quad (23)$$

The equation of plasticity (2) connects the quantities p_x and $\sigma'_{x_{av}}$ by the following dependence:

$$p_x - \sigma'_{x_{av}} = 2k,$$

and we thus have

$$p_x = 2k + \sigma'_{x_{av}}. \quad (24)$$

Solving the system of equation (23 and 24) we obtain

$$p_x = 2k + \sigma_{x_{av}} h_x. \quad (25)$$

Substituting $\sigma_{x_{av}}$ (20) in equation (25), we obtain

$$p_x = 2k + n \frac{2}{981} k \frac{rv_1 h_1 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2} h_x \frac{d\alpha}{dt},$$

where n is the dimensionality coefficient ($n = 10 \text{ l/cm}$);

We then have

$$h_x = h_1 + 2r(1 - \cos \alpha).$$

$$p_x = 2k + 2,04 \cdot k \cdot 10^{-2} \frac{rv_1 h_1 \sin \alpha}{h_1 + 2r(1 - \cos \alpha)} \frac{d\alpha}{dt}. \quad (26)$$

Substituting $d\alpha/dt$ in equation (26), we obtain the formula for determining the specific pressure along the capture arc:

$$\frac{d\alpha}{dt} = \frac{v_{x_{av}}}{\cos \alpha r}; \quad \frac{d\alpha}{dt} = \frac{v_1 h_1}{[h_1 + 2r(1 - \cos \alpha)] \cos \alpha \cdot r};$$

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$$p_x = 2k + 2,04 \cdot 10^{-2} \cdot k \frac{v_1^2 h_1^2 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2 \cos \alpha}. \quad (27)$$

During the cold rolling of metals, the so-called elastic flattening of rolls occurs in the deformation zone. This elastic flattening is accompanied by distortion and an increase in the capture arc. It also produces a pressure increase during the rolling, due to the fact that the deformation conditions of the metal become worse (due to an increase in the ratio $l:h_{av}$). Thus, during cold rolling we must take the elastic

contraction of the rolls into account when calculating the specific pressure of the metal on the roll (of the rolls on the metal). In order to obtain the total metal pressure on the roll, it is necessary to perform integration over the actual capture arc (its projection on the axis x), with allowance for the minus sign in front of the second term in the right part of equation (27), i.e.,

$$P = p_x d\alpha \int_{\alpha_0}^{\alpha_1} \left[2k - 2,04 \cdot 10^{-2} \cdot k \frac{v_1^2 h_1^2 \sin \alpha}{[h_1 + 2r(1 - \cos \alpha)]^2 \cos \alpha} \right] d\alpha. \quad (28)$$

By replacing the arc of the circle by a parabola, we obtain the following

$$p_x = 2k - 2,04 \cdot 10^{-2} \cdot k \frac{v_1^2 h_1^2 r x}{(h_1 r + x^2)^2}. \quad (29)$$

This equation may be recommended for computations performed in practice. Preliminary comparisons of formulas (27 and 28) with the experimental data yield good results.

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